Cage Culture of Salmonids in Lakes:

Best practice and risk management for Tasmania

Report to Minister for Inland Fisheries and

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1. Background to this Report

Marine cage farming of salmonid fish (salmon and trout) is well established in Tasmania. There is an established regulatory framework, administered by the Department of Primary Industries, Water and Environment (DPIWE), which controls licenses, leases and environmental conditions on cage farms and associated land-based facilities. Similarly, there is an established land-based freshwater hatchery industry primarily focussed on producing juvenile/pre-smolt fish for the marine cage sector, but also involved in producing some table fish. Again, there is a regulatory framework for this sector, with licensing, EIA and EPMP requirements, administered by DPIWE and the Inland Fisheries Commission (IFC), now the Inland Fisheries Service (IFS).

The aquaculture industry is seeking the establishment of cage salmonid culture facilities at several locations in freshwater lakes. There is, at present, no specific policy or regulatory framework in relation to this development. This report has been commissioned by IFC to address several key issues including:

- identification and assessment of any environmental risks, including any disease management issues, that are relevant to a decision to allow or disallow freshwater lake cage culture in Tasmania;
- investigation of best practice in the cage farming sector;
- proposal of a best practice environmental management approach to lake cage farming, with an emphasis on methods to reduce potential risks and impacts;
- documentation of overseas experiences with freshwater cage culture.

2. Lake cage culture overseas

Cage culture of fish is a widespread practice overseas, and is dominated by small to medium scale operations in China and Asia, focussing on domestic to commercial production of such species as tilapia etc. (Beveridge 1984). Cage culture of salmonids has been a major feature of marine aquaculture in western countries since the mid-late 1970's, expanding rapidly during the 1970's and 80's.

Cage culture of salmonids in freshwater (principally lakes) commenced around the same time and also experienced rapid expansion during the 70's and 80's. Lake cage culture of salmonids is now actively practised in several European countries (eg Poland), in Scotland, Canada and, recently, Chile. Production in Scotland commenced in the 1970's, and total freshwater loch production in 1994 was around 6000 tonnes at 50 loch sites, representing approximately 50% of total Atlantic salmon smolt production (Williamson and Beveridge 1994). Production in Ireland, initially focussed in lowland lakes (loughs) has been significantly reduced due to problems with eutrophication. Lake cage culture is currently not practiced in Norway (EAO 1997a), despite production of some 50% of the world's farmed salmon in marine facilities, following the establishment of the Nationwide Assessment of the Suitability of the Norwegian Coast Zone and rivers for Aquaculture (LENKA). Lake cage culture is well established in Chile, despite environmental problems, due to nutrient enrichment and organic waste impacts (EAO 1997b).

Lake cage culture of salmonids is recognised as a significant point source of organic waste and nutrients which cause increase in levels of water column nutrients and benthic and planktonic algae (Penczak et al. 1982, Korzeniewski et al. 1985, Phillips 1985, Phillips et al. 1986, Clarke and Phillips 1989, Stirling and Dey 1990, Maloney et al. 1991, Cornell and Whoriskey 1993, Axler et al. 1994, Kelly 1995), localised enrichment of lake sediments (Phillips 1985, Maloney et al. 1991, Cornell and Whoriskey 1993) and changes in lake fish populations and fisheries (Phillips et al. 1985, Carss 1990).

Little attention has been focussed on environmental management of freshwater cage culture globally, with virtually all the management emphasis being placed on marine farming. There has been general community concern over the environmental impact of cage culture in both marine and freshwater, resulting in a number of reviews and enquiries (Phillips et al. 1985, NCC 1990, EAO 1997 a - c, Weston et al. 1996, Clarke and Phillips 1989, McLay and Gordon-Rogers 1997).

The regulatory and management history of lake cage culture in Scotland is of particular interest. Scottish lake cage culture commenced well before a suitable environmental regulatory framework was in place. During the 1970's and 80's, local councils, with advice from river protection authorities, were responsible for licensing cage farms. A licence/consent to pollute system already existed for waste water management (under the Scottish Control of Pollution Act 1974, and the Water Act 1989), but this was not applied to lake cage culture until the late 1980's. The consent systems has only become fully active since the Scottish EPA (SEPA) was formed in the late 1980's. A large number of farms had become established before the regulatory context was clarified, and authorities were reluctant to set discharge limits that could then curtail commercial activity (Clelland SEPA pers. comm.; Hennessy Institute for Aquaculture, University of Stirling, pers. comm.).

Several factors have made the management of lake cage farms complex in Scotland. Few data were collected on the nutrient/trophic status of lakes prior to farm establishment, and many lakes were already affected by multiple sources of disturbance including forestry, farming, and peat mining, as well as some inputs from waste water treatment plants (WWTP's). Thus, while many lochs were oligotrophic, a considerable number already had enhanced nutrient fluxes (NCC 1990).

Under the Consent system, approvals and licensing under Scottish regulations have depended on concentrations or loads associated with waste water emissions i.e. 'output' or 'end of pipe' management. Since open-cage (i.e. net pen) farming cannot be readily managed in this way, a new approach had to be developed to regulate the potential for environmental impact. It wasn't until the mid 1980's that a modelling-based approach was developed, articulated by Beveridge (1984), based on mass balances, nutrient loadings, and nutrient-algal models developed by Vollenweider (1969), Dillon and Rigler (1974) and OECD (1982). In addition, assessments were made by comparison against environmental standards, especially for water quality (SEPA 1997).

Little consistent monitoring data were collected until the early 1990's by which time, most of the industry had been established and there was little scope for assessing the degree to which the nutrient and trophic state of lakes was actually determined by an individual cage farm facility. Cage farms are now licensed using biomass production limits, set by the use of the Beveridge modelling approach which takes lake characteristics into account. For many lakes this approach is deemed to work well (Clelland, SEPA, pers. comm.). The models only account for water column water quality dynamics, and depend on regional nutrient-chlorophyll relationships to predict water column algal biomass. They do not model biological transfer of nutrients, sediment dynamics or sediment-water interactions (Kelly 1995). Lakes with complex hydrology, multiple disturbances including nutrient inputs, and high degree of thermal stratification tend to be poorly modelled using this approach.

Recognising these constraints, monitoring programs have been established to evaluate changes in both water quality and characteristics of benthic (bottom) sediments, along similar lines to those used in marine farm monitoring. A limit to the spread of changes to benthic sediments is established (typically 25 m outside the cage farm site), and changes in farm practices are negotiated when that limit is exceeded.

There has been little active management of disease risks associated with lake cage farms, either in Scotland or Canada, though the potential for disease transfer between domestic and wild fish is recognised (Weston et al. 1996).

Overall, the Scottish lake cage salmonid industry is well established though with a variable environmental record and with several lakes experiencing nutrient enrichment and biological degradation. Lakes associated with cage farms have only been actively monitored since the late 1980's/early 1990's, and calls have been made to improve modelling to assist in regulation and monitoring (eg Kelly 1995, Gavine et al. 1995). There is a Fish Farm Advisory Group (FFAG) which is developing a 'Procedures Manual for the Regulation and Monitoring of Freshwater Fish Farming' (made available in draft form for this review). This manual details the processes for application and assessment for licenses, setting consent limits, monitoring and review. It does not articulate a best practice approach to environmental management of freshwater fish farming.

The Scottish lake cage industry has been supported by active research mainly conducted by several individuals from the University of Stirling, Institute for Aquaculture, and it is this group that have been responsible for the majority of investigations into environmental aspects of management of lake cage farms.

Overall, the Scottish lake cage culture scene has a history in which the industry was established and rapidly expanding before regulatory tools had been developed to manage it. Much of the subsequent developments in environmental management were suitable for licensing new sites, but unable to effectively deal with the large number of established farms using open cage farming, or to assess the degree of impact associated with them. Much of the results of research and monitoring associated with the environmental performance and impact of the Scottish lake cage industry is however of significant value in assessing best practice for the management of this industry sector in Tasmania.

3. Marine cage farming in Tasmania – environmental issues and management

This section is intended to provide a brief overview of environmental issues associated with marine cage farming in Tasmania and their management, as it is relevant to the potential for lake cage culture.

Marine cage farming has been established for a decade in Tasmania, and the following environmental issues have been recognised:

- Changes in water quality resulting from waste feed and fish excretion;
- Associated changes in benthic sediment composition, chemistry and fauna;
- Changes in local fish population composition and density associated with wild fish associated with farm structures, escaped or releases domestic fish at or within waters associated with the farm site;
- Risk of disease (bacteria, parasites, viruses) transfer from wild fish to domestic fish and vice versa;
- Limitation of access by the public to farm lease sites;
- Visual impacts of farm infrastructure.

A planning framework has been established under the Marine Farm Planning Act (1995), which provides for the formulation of plans for zones and sites which describe the geographic extent of farm sites, carrying capacity controls, monitoring requirements, and the principles of management of disease, waste, visual impact, access and land use impacts. Marine farming licenses are issued with a suite of conditions which include requirements for compliance with specific environmental standards (including water and sediment quality), conduct of environmental monitoring, records and reporting. Baseline surveys are also required, under a set of prescriptions issued by the Marine Farming Branch of DPIWE. While a regulatory process exists for freshwater salmonid aquaculture, a planning approach with several of the features of that used for marine cage farms would be of significant benefit.

Monitoring of marine cage sites is largely restricted to:

- Collection of 'baseline' water quality, sediment composition and faunal data prior to site establishment (though not for farms established in the early 1990's);
- Routine collection (as a licence condition) of video and sampled data on benthic sediment conditions and composition.

Little emphasis is given to routine water quality monitoring, largely due to the complexity of hydrodynamics in the marine environment, coupled with the poor understanding of nutrient driven processes in Tasmanian coastal waters. Studies have recently been conducted to assess the overall nutrient dynamics of the Huon estuary (an intensively farmed zone). This will be used to assess the relative contribution of cage farm facilities to the overall nutrient budget of the estuary (CSIRO Division of Fisheries and Oceanography, in progress) in the context of algal bloom risk.

4. Environmental risks and impacts of lake cage culture of salmonids

The types of impacts observed in freshwater lakes from cage farming (see section 2) are also observed in marine cage farms (Gowen and Bradbury 1987), though freshwater environments differ in several key aspects. Firstly, most lake cage farm sites have lower current velocities and higher potential for organic sedimentation than in marine sites (Weston et al. 1996). Settlement velocities for both coarse (waste feed) and fine (faecal waste) organic material are significantly lower in freshwater than in saline waters (Elberizon and Kelly 1998). In the marine environment, nitrogen is a key limiting nutrient. In freshwater both nitrogen and phosphorus, though particularly phosphorus, are limiting nutrients for primary production and hence changes in algal biomass. There are therefore differences between the marine and freshwater environments in the relationship between cage farming and environmental impacts.

In the marine environment, there is an emphasis on assessing change to benthic sediment composition and fauna. In freshwater, while benthic sediment impacts are also potentially significant, the overall impact of cage farms on lake nutrient status ('nutrification') and any resulting changes in algae and related ecosystem processes ('eutrophication') are equally, or more, important (Weston et al. 1996). There is ample evidence of local and lake-wide nutrification resulting from salmonid cage farms. There is also some evidence of localised, and in specific cases, lake-wide eutrophication, but this biological response to nutrification is highly dependent on lake characteristics, farm biomass and farm management.

The following environmental risks are recognised to be associated with lake cage culture of salmonids:

4.1 Nutrient enrichment

One of the primary impacts of aquaculture is enrichment of the water column with nutrients (nutrification) resulting from release of phosphorus (P) and nitrogen (N) from fish faeces, and waste feed, as well by direct excretion by fish (especially for ammonia). This environmental issue has been well recognised by the freshwater cage industry sector for many years (eg Harvey and Laird 1988), and is a direct consequence of the 'open' nature of lake cage culture, in which waste is released without treatment or active management. Feed losses from cages form a high proportion of total solid waste load from salmonid farms (Phillips et al. 1985, Kelly et al. 1996). Total P released from land-based and cage farm facilities has been reported as ranging between 8 and 40 kg per tonne of fish biomass produced, typically around 10 kg/tonne (Gavine et al. 1995, Kelly et al. 1996). In many low nutrient (oligotrophic) waters, cage farms may be the single major source of P, although this will vary considerably depending on lake characteristics.

Use of fish production/biomass limits to minimise/control input of nutrients and organic enrichment to lakes is practised in Scotland, Canada and the USA (e.g. NCC 1990), and is a key 'input' control of nutrient loadings to lakes in open cage systems.

Most P and N loss to waste is due to waste feed, low feed nutrient assimilation (and hence excretion), and waste excretion. Only some 25% of the P and N in typical feeds is assimilated into the fish, with 65% and 10% of P being directly excreted to the water column (Bergheim et al. 1991). Up to 65% of P and 10% of N is associated with particulate matter, the majority of which is deposited as benthic sediment. Some 6 – 12% of P may be released to the water column by leaching from sinking waste pellet feed and faecal material (Weston et al. 1996).

Waste feed and faecal material account for the majority of waste organic loading, and associated nutrients, in sediment accumulated on the lake floor (Weston et al. 1996). Most of this is no longer bioavailable (Phillips et al. 1986), though this is dependent on lake mixing characteristics (particularly the frequency and intensity of water column stratification), and bioturbation (e.g. biological 'release' of nutrients from sediments).

There has been a trend toward improving feeding efficiency and feed quality throughout the salmonid aquaculture industry (both marine and freshwater), largely due to the resulting improvement in production efficiency and costs .This has been demonstrated to reduce waste and nutrient loadings (Kelly et al. 1996, Gavine et al. 1995, Kelly and Cripps 1999a).

4.2 Enhancement of algal growth

Enhancement of nutrient levels in lakes may result in enhanced algal growth (eutrophication) under certain conditions. Filamentous and/or planktonic algal populations may respond to elevated P and N concentrations, when those nutrients are limiting for algal growth, and when the forms of P and N are bioavailable. Massik and Costello (1994) observed that 82% of P in effluent from salmonid farms was directly bioavailable to phytoplanktonic algae. Thus, not only does salmonid aquaculture represent a significant point source of nutrients in lake systems, but the nutrients are in a highly biologically available form.

Other limiting factors also contribute to algal population responses to nutrient enrichment. Significant factors include:

- light availability – controlled by water clarity, water colour and lake mixing characteristics;
- temperature – with responses being higher at higher temperatures;
- availability of other potentially limiting elements (e.g. silica for diatomaceous algae).

Most Tasmanian lakes are primarily P-limited (Davies 1992), and occasionally N limited. A mean annual water column concentration of 20 µg/l total P is regarded as an upper limit beyond which significant signs of algal eutrophication become evident in Tasmanian lakes, a level set as a target for lake remediation (Davies 1992, Sanger 1992).

Algal growth in many Tasmanian lakes and estuaries, especially waters with high colour levels (e.g. the 'humic' dystrophic lakes typical of western Tasmania), may frequently be limited by light availability (Bowling et al. 1986, Hallegraef pers. comm.). In such waters, light of photosynthetic wavelengths does not penetrate far into the water column, and in mixed lakes algae spend significant periods of time at depth in a limiting light environment.

Most Tasmanian lakes are 'oligotrophic' i.e. nutrient poor with relatively low algal biomass. There are several naturally 'mesotrophic' lakes (eg Lakes Sorell, Crescent), typified by being shallow, well mixed and with extensive macrophyte communities and abundant phytoplankton. A small number of Tasmanian lakes have been eutrophic at some time (eg Craigbourne Dam). These are usually artificial storages, or modified lakes, and have disturbed catchments with high external or internal nutrient loads. Several lakes have been associated with algal blooms (both blue-green and green) for varying periods, and have required intensive and costly management. Recent (1980's to 90's) experience indicates that shallow, clear Tasmanian lakes are highly susceptible to changes in nutrient status. Lagoon of Islands experienced a major algal bloom (water column chlorophyll a levels between 20 and 100 µg/l) following a period with TP concentrations consistently within the range 20 – 60 µg/l (Sanger 1992, HEC unpub. data).

4.3 Organic enrichment of benthic sediment

Changes to the characteristics of sediments beneath and in the vicinity of cage facilities are well documented in the marine environment, both in Tasmania and overseas (e.g. Gowen and Bradbury 1987, Johannessen et al. 1994). Waste organic material is frequently observed accumulated as deposits from 5 to 40 cm thick under marine and freshwater cages. These deposits are associated with development of surface bacterial and fungal films (e.g. *Beggiatoa* in marine farms), anoxic sub-surface conditions with high respiratory demand and the potential for methane and hydrogen sulphide production. The benthic fauna is often impoverished, and typified by species associated with organic enrichment.

These impacts, generally regarded as environmental degradation, may be observed for distances up to 40 m away from cages, depending on current velocities. Such impacts on benthic sediments are a common feature of overseas and Tasmanian marine cage farms. In freshwater cage farms overseas, benthic impacts are rarely observed beyond 25 m from cage sites (Phillips et al. 1986, Weston et al. 1996) - the benthic sediment ‘footprint’ in lakes tending to be smaller, primarily due to the lower water velocities compared to many marine sites.

Benthic sediments are intensively monitored, as part of environmental management of most salmonid cage facilities in both marine and freshwaters, and there are a number of site management approaches have been developed to reduce or minimise the impact. These include moving cages or whole farms between locations to allow some natural restoration of impacted benthic areas (‘fallowing’), as well as active pumping or dredging and dispersal and/or land disposal of accumulated material.

4.4 Changes to wild fish population densities and production

Accumulations of fish in the vicinity of salmonid cage farms have been documented in both marine and freshwaters (Phillips 1985, Phillips et al. 1985, Carss 1990, Weston et al. 1996). These populations comprise both wild fish (e.g. wild trout) and domestic fish that have escaped or been accidentally or intentionally released. These fish populations are known to spend considerable times adjacent to the cage farm, rely to a considerable extent on waste feed in their diet, and may carry similar pathogens or parasites to the cage stock (Phillips et al. 1985, Carss 1990).

In addition to local fish population aggregation, the overall productivity of a lake may be enhanced by the presence of a cage farm facility, resulting in enhanced growth rates of wild fish (Phillips et al. 1985). The lake fish population is also characterised by increasing numbers of previously domestic fish which range throughout the waterbody.

An additional feature of salmonid cage farm aquaculture is the enhanced aggregation of predatory species in the vicinity of the farm, which may become partially dependent on the presence of farm and aggregated wild fish. In the freshwater environment, this may include mammals (e.g. water rats), and birds (e.g. eagles, cormorants), which may require active management.

4.5 Disease transmission

While disease transmission between domestic and wild fish populations is a known environmental risk associated with land-based freshwater aquaculture (Weston et al. 1996), cage farms are generally regarded as having an enhanced potential for pathogen and parasite exchange, largely due to the greater probability of contact between domestic fish and wild fish aggregated around cage sites. While this is not a major issue at present, given the low salmonid disease risk in Tasmania, it has the potential to present greater risks in the future if significant pathogens are established in the state.

Parasite, virus and bacterial exchange between wild and domestic stock has been reported in Australian marine farms (K Ellard DPIWE pers. comm.). Examples include:

- 'Birna virus' with both domestic fish being recently infected in Macquarie Harbour – thought to be a transfer from wild to domestic stock;
- Amoebic gill disease – an amoebic infestation of gills under specific water quality and salinity conditions, again emanating from the wild;
- Fluke infestations have been observed in caged snapper in WA, again implying transfer from wild to caged fish.

In freshwater, there are a few diseases common to wild and domestic stock, and some form of exchange is therefore implied:

- *Yersinia ruckeri* (enteric redmouth) was observed in domestic hatchery stock in Tasmania in the late 1980's, but was subsequently also found in wild brown trout populations;
- *Aeromonas* bacterial infections are a common feature of domestic freshwater fish in hatcheries, with clinical disease outbreaks particularly following periods of stress. These bacteria are ubiquitous in the freshwater environment.
- other parasitic (eg 'icth') and fungal diseases are well known in the freshwater, and again are ubiquitous, with disease outbreaks usually a feature of poor fish husbandry and stress.

There is no evidence of disease transfer from domestic to wild fish populations in Australian aquaculture to date. Overseas experience has not demonstrated any disease risk for wild populations specific to cage farms, nor any major disease risk particularly associated with cage farms. While some evidence exists of microbial pathogen transfer from domestic to wild fish (eg *Yersinia* and IHN), Weston et al. (1996) state that there is no evidence that disease outbreaks in farmed fish have raised pathogen levels in wild fish to levels where clinical disease is observed. Most disease organisms found in domestic stock are also found in wild fish, though domestic fish are more susceptible to clinical disease outbreaks (through high densities, stress and rapid transmission).

Recent records of infectious salmon anaemia (ISA) in Scotland indicate the spread of the disease via cage farms in Scottish marine and freshwaters (identified as coming from a single farm source). The virus has also been found in both marine and freshwater fish in the vicinity of infected farms (Scottish Executive 1999). This implies that there has been transfer from domestic to wild stock. Overall however, whether land-based or caged, farmed fish tend to be infected from the wild, and that population may then act as a possible focus for infection back to the wild.

Cage farm facilities may require specific disease management prescriptions, with emphasis on minimising the potential for transfer of disease to wild fish, and reducing their potential for acting as a focus for re-infection. Reducing emission of organic matter by filtration of solids, to which pathogens may adhere, will also assist in reducing risk of disease transmission (K Ellard DPIWE pers. comm.). This applies to both land-based and cage farms, though particularly relevant to cage farms as waste feed and associated organic material form a significant portion of the diet of wild fish adjacent to cages (Phillips et al. 1985, Carss 1990). Reducing the potential for direct or close contact between caged and wild fish is also important.

Protozoan parasite transmission from and to wild fish is a common issue in both freshwater and marine salmonid aquaculture. It is typically managed by use of formalin, some of which is discharged to the receiving environment.

5. Environmental best practice

There is no established best environmental management practice framework for the marine or freshwater salmonid cage-farming industry in Australia, nor overseas. Limited best management practice guidelines exist in the salmonid aquaculture industry, principally focussed on the production and marketing components of the industry. There has also been a lack of progress in the development of management and technological options specifically for the minimisation of environmental impact of salmonid cage aquaculture. Open-cage systems still dominate the industry after 30 years, despite acknowledged impacts from soluble and solid waste emissions.

A recent workshop held in Victoria, Australia, (Ingram 1999) was designed to identify best practice management (BMP) in land-based salmonid farming for the improvement of environmental performance, though guidelines are yet to be produced. Kelly and Cripps (1999a), at that workshop, identified two core components of BMP for reducing environmental impacts of land-based salmonid aquaculture. These are:

- limitation and treatment of waste outputs, through treatment of waste waters; and

- reduction of inputs to the production cycle, through feed controls of feed quantity and quality (composition).

Recent emphasis has largely been on input controls (Kelly and Cripps 1999b), though both of these are core issues for BMP in lake cage aquaculture.

A best practice framework focussed on environmental outcomes coupled with appropriate planning and licencing tools is a highly desirable approach to environmental management of any proposed Tasmanian lake cage culture industry. Until recently, the focus on water quality management in Tasmania has been on 'output' (end of pipe) discharge monitoring (under the Environmental Protection Act 1974 and associated Regulations). Recent developments in regulation of both lake cage and land-based salmonid farming overseas have included a number of 'input' prescriptions aimed at reducing production of waste solids and nutrients. These include biomass or production constraints, and constraints on feed composition and quantity. These controls are more consistent with the new focus on receiving water condition and the hierarchy of waste management, emphasising reduction in waste production and reuse, articulated in the Tasmanian Environmental Management Pollution Control Act 1994 and the State Policy on Water Quality Management 1997.

In discussing BPM for lake cage culture one must be aware that:

- there has been no industry vision of environmental BPM;
- world's 'best practice' in this industry at present does not represent high quality environmental performance. Open-cage culture is the dominant form of farming in lakes, and little advance has been made in relation to waste management other than to:
  - limit production rates, based on guidelines set by government;
  - minimise waste generation by decreasing FCR's, increasing feeding efficiency and decreasing feed nutrient content – a regulatory approach which has not yet been widely adopted.

Industry has invested considerable effort in reducing feed wastage and improving feed conversion rates in order to reduce costs, and in optimising stocking densities and site selection to maintain suitable water quality for salmonid growth. All of these also have the coincidental benefit of reducing environmental impact on the receiving waters, again being of benefit in maintaining suitable conditions for production. However, there is a limit to which these efforts can reduce waste and nutrient emission. Active management of wastes is therefore required to achieve environmental best practice.

Thus, improvements in feed quality and feed management have resulted in reductions in solid waste emission by up to 50% in land-based Victorian salmonid farms (Ingram 1998), but further reductions in waste production are needed. Some operators in the Tasmanian land-based salmonid industry have recently made significant efforts to remove solid waste from hatchery effluents using newer technologies such as hydrocyclones, and wedge wire screens (with land-based treatment and/or disposal), combined with partial water recirculation. A key principal is the mechanical removal of solids as close as possible to their source, to minimise the potential for breakdown to smaller less manageable size fractions and leaching (Ingram 1999). There are also moves to improve the capacity and efficiency of settling pond designs by some operators. Adoption and development of new waste treatment and management technologies is also required in the cage farm industry if it is to operate in sensitive environments, including freshwater lakes.

Overall, best environmental practice when managing a potentially environmentally damaging industry is to prevent its establishment, as has happened in Norway (EAO 1997a). If the precautionary principle cannot be applied, then strong limitations should be imposed on its initial operations, with developmental trials on small scales. During this period, planning and management tools should be further developed.

An initial step in BPM for lake cage culture, if it goes ahead, is to establish conditions under which it can and cannot operate. The development of criteria for selecting lakes suitable for cage culture is a first step. Following this, both 'input' and 'output' and prescriptions must be developed and put in place in order to minimise waste production and associated environmental risks, as well as prescriptions for monitoring and surveillance. These are described below.

5.2 Site Choice

5.2.1 Lake type

A simple classification should be developed of lakes based on their potential environmental suitability as sites for cage aquaculture. Key criteria for the exclusion of cage aquaculture from lakes on environmental grounds should include:

- Lake depth – shallow lakes with depths within or approaching euphotic depths (depths within which light availability is sufficient to sustain active plant/algal growth) would be at risk of significant algal responses to nutrient enrichment;
- Lake water exchange rates – lakes with low water exchange ('flushing rates') are at greater risk of accumulation of significant in-lake nutrient loads and sediment enrichment;
- Lake stratification – lakes with strong, annual thermal stratification are at risk of significant release of nutrients into the water column when stratification breaks down and mixing occurs, particularly when bottom (hypolimnetic) waters become de-oxygenated due to organic enrichment.
- Water colour – lakes with high colour levels (and hence light adsorption) limit the ability of planktonic algae to respond to nutrient enrichment, as algal growth is light limited at depth in mixed lakes. Similarly, there is strong light limitation of benthic algal growth at depth. Lakes with low levels of dissolved organic carbon (DOC) and hence with more intense and blue-green light environments should not be selected as sites for cage culture.
- Presence of significant conflict with other uses – lakes in which there is a significant potential conflict with abstractive and non-abstractive users should be avoided as sites for cage farming.

- Presence of threatened species – as impacts on water quality and disease risks are currently not known, lakes in which threatened species have been identified are not suitable sites for establishing cage farms.

Key criteria for the exclusion of cage aquaculture from lakes on practical grounds are as follows:

- High lake level variability and lake exposure – sites with high levels of lake variation (e.g. caused by Hydro operations) and with high exposure to frontal system winds may not provide sufficient security for cage farm sites;
- Polluted lakes or those with potential for pollution – several lakes or lake basins (eg Lakes Burbury, Pieman, Gordon and Rosebery) may have metal levels too high for optimum growth and/or survival and/or market acceptability of intensively reared salmonids;
- Poor access to shore based facilities – ready access to shore facilities is a key factor in site selection, as well as distance from marine cage and land-based hatchery and/or processing sites.

5.2.2 Within lake

Key criteria for the exclusion of cage aquaculture from sites within lakes on environmental and practical grounds are as follows:

- Shore exposure and 'fetch' – see above, with respect to site security and risk of damage.
- Site water movement characteristics – sites with inadequate current speeds may be unsuitable for the farm fish and may experience enhanced deposition of benthic sediment.
- Access to shore based facilities – see above.
- Other exclusions – a number of sites within lakes may be unsuitable for aesthetic reasons, conflicts with other uses, and due to constraints set by authorities managing the lake (eg Hydro power station intakes and outlets and spillways; other water offtakes).

In essence this excludes a significant proportion of Tasmania's lakes, for example:

- all Central Highland lakes (as they have low colour and are generally shallow, and have significant recreational fisheries of high value);
- all small lowland dams and reservoirs with limited depth and water exchange, due to the potential for eutrophication;
- all storages primarily managed for drinking/domestic water supply, due to the potential for enhanced treatment costs resulting from changes in water quality;
- all other lakes with low water exchange rates;
- all Hydro lakes managed as 'head storages', with high lake level variation.

Lakes that may still be suitable for limited development of cage culture include deep, cool, run-of-the-river Hydro storages with high colour, limited or no thermal stratification, high water exchange rates and current speeds. In essence, this limits development to lakes in the lower section of the Derwent scheme and in the Mersey-Forth Hydro scheme, though not all storages within those schemes.

5.3 'Input controls'

5.3.1 Biomass/production limits

If a suite of potential lakes has been selected for trial cage sites, further investigations are required to adapt models to quantify production limits. The best approach applied to date is that described by Beveridge (1984) and Kelly (1995), in which a simple mass balance model is used in combination with locally derived nutrient-algal models.

The mass balance modelling approach used by Beveridge and Scottish authorities (eg SEPA, Highlands and Islands Enterprise) uses modified forms of nutrient-algal models developed by Vollenweider (1969), Dillon and Rigler (1974) and OECD (1982). Some improvements in nutrient-algal modelling have been made by taking lake mixing characteristics into account (e.g. Riley and Prepas 1985).

Davies (1992) showed that 45 Tasmanian lakes surveyed for nutrients and planktonic algae followed similar correlative relationships to those described by Dillon and Rigler (1974) and Vollenweider (1969). In addition, the relationship between water column nutrient and chlorophyll levels in Lagoon of Islands, central Highlands, over a two year period during the development of a major *Staurastrum* algal bloom, was also similar to that derived from the spatial survey of Tasmanian lakes. It therefore appears feasible to develop relatively simple models similar in form to those described by Beveridge (1984) and Riley and Prepas (1985), for Tasmanian lakes.

Kelly (1995) found variability in the ability of mass balance models to predict nutrient status of lakes with cage farms. Improvements in overall mass-balance model predictions are needed to account for situations with multiple nutrient inputs, and care must be taken to ensure model and monitoring data are based on appropriate time intervals (Kelly 1995). There are alternative modelling approaches for assessing relationships between farm characteristics (including biomass and feed rates) and lake nutrient and organic sediment loadings, the most advanced being ones which are based on fish bioenergetics (Axler et al. 1993). These models predict TN, TP and solid loads with variable success, and the simpler mass balance approach is preferable at this stage for planning purposes.

In using the relatively simple mass-balance approach in deriving production limits for lakes (Kelly 1995), and subsequently for monitoring departures from or consistency with model predictions, monitoring data must be collected on lake nutrient and algal (chlorophyll) status, as well as on feeding rates, feed quality and farm biomass and production figures. Data must also be collected on both inflow and outflow concentrations and loadings of nutrients, as well as physical data relating to the lake (annual rainfall, bathymetry, inflows and outflows). Licence conditions must be imposed to require routine collection of such data.

The following is recommended:

- existing field data on lake nutrient and chlorophyll levels (collected by the Hydro and IFC between 1988 and 1999) be supplemented for suitable lakes (eg Mersey-Forth and Derwent systems); and that
- lakes within those systems be 'screened' for trophic status;
- models be developed for the remaining lakes which describe water and nutrient mass balances and nutrient-chlorophyll relationships (see Beveridge 1984, Kelly 1995);
- existing data on lake storage volumes and water inputs be used to evaluate possible cage farm biomass limits for selected lakes, using a range of waste loadings based on small scale trial data or data derived from Tasmanian marine farms.

5.3.2 Management of feed quality and quantity

Most P, N and organic output from cage farms is due to waste feed, low feed nutrient assimilation (and hence excretion), and waste excretion. Not surprisingly, total P and N waste loadings per tonne of fish produced at cage farms are related to food conversion ratio (FCR), and P and N content of the feed (Gavine et al. 1995). Thus, while total nutrient release from cage farm sites is strongly controlled by fish biomass, it can also be managed by:

- Minimising food conversion ratios (FCR's), through use of high fat, low protein foods (Johnson and Wandsvik 1991) – improvements in feed quality have resulted in decreases in FCR from 1.5 to 3.5 down to 0.9 – 1.2 over the past decade (Wee 1999);
- Maximising the efficiency of feeding, through use of controlled feeding regimes to reduce feed loss (e.g. using 'Aquasmart' technology);
- Reducing the P content in feed, through using ingredients with a lower P content (e.g. soya meal, low-ash fish meal or HND or high nutrient dense feeds, Cho et al. 1991) – P content has been observed to range from 5 to 23 mg/kg feed (Gavine et al. 1995), and in Denmark is regulated to be less than 10 mg/kg, (Jensen 1991);
- Reducing feed waste loss, through reducing feed dust content (through use of extruded pellets, Johnson and Wandsvik 1991):
- Maximising feed P assimilability, through use of appropriate feed ingredients;

- Capturing waste feed/faecal material and minimising deposition in the lake, by the use of bag culture techniques and/or aprons.

The recent trend to use newly developed low nutrient content feed combined with low FCR's has been shown to result in reduction in total P waste loadings by around 50% (Gavine et al. 1995). A trade-off between P content, FCR and fish production is required to ensure effective fish production rates while minimising waste nutrient loads.

Best practice in this area focuses on reducing waste from feeding by controlling both the quality of the feed and the quantity of feed supplied and eaten.

5.4 'Output controls'

5.4.1 Cage management and waste treatment

Best practice for minimising environmental impact of a cage farm should focus on minimising contact with the lake environment in order to:

- reduce nutrient and organic enrichment of the lake water column or bottom sediments;
- reduce the potential for disease transfer between domestic and wild fish;
- reduce the potential for discharge of other materials to the lake.
- reduce behavioral changes in wild fish (*eg*, crowding the cages to feed).

Trials being conducted in Tasmania in the marine environment by Aquatas Pty Ltd, in partnership with Future Sea Technologies (Canada) suggest that completely enclosed, 'bag' culture SEA (Sustained Environment Aquaculture) systems may allow high culture densities, coupled with reduced water and nutrient discharges and the possibility of solids removal from waste water discharge. Such systems are characterised by a pumped input of water to a completely enclosed 'bag' from the surrounding water, with a discharge at a single point, through a series of filters and/or sumps designed to trap waste solids. This system has the potential to significantly reduce waste organic and nutrient loads. There is also potential for land-based waste treatment where bag outflows and sumps are adjacent to lake shorelines. Bags also reduce the potential for close contact between domestic and wild fish, and predators. Trials to date have been limited, and further development of this technology is required to ensure effective management including reduction in waste loads.

Aprons and cones suspended below cages in order to catch settled solids have been trialled (Behmer et al. 1993) and trials continue in Scotland (McClelland SEPA pers. comm.). There is little evidence to date that this technology is effective or practical at 'farm' scale, as solids recovery is inversely related to water column velocity, and sites are generally selected for higher current velocity to ensure optimum growth conditions in open cage systems, but further research and development is warranted (Weston et al. 1996).

5.4.2 Site management

Best practice for minimising environmental impact of a cage farm should include appropriate site selection to maximise dilution and dispersal of any waste discharges (see above under 5.2). Where monitoring indicates significant build up of organic sediment in the immediate vicinity of cages, and particularly where organic sediment is observed beyond an agreed distance from the cage site (eg 25 m), pumped removal of deposits (for land-based treatment waste) and/or dispersal into higher velocity areas could be conducted. Appropriate rotation of sites within lakes should be conducted to ensure at least partial recovery of any impacted benthic sediment by natural biological processes. This practice of 'fallowing' is a frequent feature of site management in marine cage farming.

5.5 Monitoring

Best practice in monitoring will be to design a program which addresses:

- Water quality risks – nutrient status, dissolved oxygen (DO), algal abundance;

- Benthic sediment enrichment – redox, nutrient loads, organic content, particle size distribution, benthic macroinvertebrates, surface appearance;
- Disease risks – disease surveillance of domestic and wild fish populations, in compliance with the Tasmanian Fish Health Surveillance Program.

Monitoring should have a significant 'pre' site establishment component, with the objective of establishing 'benchmark' data for future comparison, as well as a routine on-going surveillance component.

5.5.1 Pre site establishment monitoring

As indicated previously, at least 12 months, preferably two years, of water quality data should be intensively collected from lakes that are candidates for site establishment. This must include sampling through the water column (at a minimum of 3 locations) at some 4 to 8 sites within the lake, depending on the lake morphometry. Sites should be located so that an overall assessment of lake water quality conditions is obtained. At least one site should be established in the immediate vicinity of the proposed cage site. Sampling through the profile should be conducted at intervals sufficient to obtain an indication of overall conditions in the water column, as well as to ascertain the occurrence of any stratification (i.e. the presence of any thermocline or oxycline).

Sampling should also be conducted at all significant lake inflows and outflows to assess input and export loads of nutrients. Flow records should be continuously recorded at all significant inflows and outflows, as should lake level. The bathymetry of the lake should be known well enough to estimate volume - lake level relationships.

All water sampling should be conducted at 2-monthly intervals.

Water from each sampling location should be analysed for N and P nutrient forms including TN, TP, nitrate, ammonia, dissolved reactive phosphorus (DRP). Turbidity, colour, total suspended solids (TSS), conductivity, dissolved oxygen (DO) and temperature should also be measured.

In addition, a suite of potential cage sites should be assessed for current velocity, DO and temperature profiles, again sampled two-monthly.

Data should be analysed to:

- develop a summary baseline data set for future trend assessment;
- compare the candidate lakes with revised nutrient-chlorophyll models (see above), and integrate the data with those models if compatible;
- assess suitability of individual sites for cage locations;
- derive limits for farm biomass and feed rates for the target lake(s), for given scenarios of feed composition and FCR.

Benthic sediment should be collected at all sites at which water quality is measured (including potential farm sites), on one occasion per year (during summer). Sediment should be characterised by sampling (grab/core sampling where appropriate), and where practical, video footage collected as a baseline for assessing changes. Protocols similar to those used in marine cage farm benthic sediment monitoring should apply (recognising some of the practical difficulties). Where fine sediment exists, it should be assessed for grain size, redox, organic content and macroinvertebrates.

Disease status of the resident fish populations should be assessed by a program of dedicated sampling, in order to develop a baseline for future comparison.

5.5.2 Routine surveillance monitoring

Once a site is established, then routine monitoring should be conducted with the same intensity as the 'pre-' monitoring, for at least two years following site establishment. Data should then be formally reviewed and a revised program agreed on and conducted as part of ongoing licence conditions. Biomass/production and feed limits should also be reviewed every two years, with the possibility of reducing or limiting production clearly recognised if the monitoring data fail the specified criteria.

Sediment assessment should follow a similar sampling schedule to that used in marine farm sites viz. biennial repeat of benthic sampling and analysis, and six-monthly video surveys. Assessment at established cage sites should be conducted using at least two transects with their mid-points under the farm site, and passing at least 200 m from the edge of the farm/lease. These data should also be used to assess the ‘spread’ of the affected sediment area. Where the affected zone (i.e. with enriched organic sediment) is beyond a specified distance (eg 35 m) outside the farm site, licence conditions must be changed in order to reduce/limit feed use or production, or for the use of other methods of reducing waste emissions from the site.

5.6 Disease management

Disease management in Tasmanian salmonid industry operates under several regulatory and management tools, including: Animal Health Act 1995, the Animal Health Regulations 1996, the Animal Disease Emergency Management Plan 1995, the Inland Fisheries Act 1995 and Tasmanian Fish Health Operational Plans (currently in preparation). There are also a range of regulatory and management tools operating nationally, including the recently prepared AQUAVET plan, as well as a consultative committee on exotic animal disease, which serves a surveillance and advisory role on the status and management of exotic disease and epizootics for all livestock, including fish. Within Tasmania, a co-ordinated fish health monitoring program operates across the aquaculture industry, articulated in the Tasmanian Fish Health Surveillance Program (1998-99), overseen by the Chief Veterinary Officer and the Fish Health Planning and Advisory Group. A formal set of procedures for management of fish health emergencies has been articulated in the Tasmanian Fish Health Emergency Management Plan (1997), based on the Animal Disease Emergency Management Plan. Fish health emergencies include major threats to the industry (including industry viability, market access and industry’s “disease free” image) from disease or environmental hazards, and all emergencies fall under the technical control of the Chief Veterinary Officer. Provisions of both the fish health surveillance and the emergency management plans would need to be extended to cover cage farms.

The Tasmanian Fish Health Emergency Management Plan has a strong focus on protection of the aquaculture industry. There is little in the Plan that deals with the issue of managing risks to the environment (eg wild fish) resulting from disease emergencies within the industry (eg introduction of pathogens). This is an issue that should be specifically addressed in future versions of the Plan, particularly with regard to roles and responsibilities of various government agencies and their actions in relation to the protection of the aquatic environment (including the recreational trout fishery) in the instance of a fish health risk emanating from the industry. This is relevant to both land-based and lake cage salmonid culture.

Best practice for disease management on-farm should include:

- use of immunised fish (eg to *Vibrio* and *Yersinia*) wherever possible;
- reducing risk of disease transfer between age classes (eg between 2-3 year fish and smolt) by using separate sites for different age classes;
- maintaining high water quality within cage sites;
- filtering waste solids and removing them from the host lake (eg by use of bag culture techniques with appropriately designed and maintained filter/sump facilities);
- maintaining active surveillance of disease status of both domestic stock and receiving lake wild fish populations;
- complying with all aspects of the Tasmanian Fish Health Surveillance Emergency Management Plan and the Tasmanian Fish Health Emergency Management Plan 1997, as well as recording all fish transfer in compliance with the requirements of Inland Fisheries Service.

5.7 Chemical use

All use of chemicals should be minimised. Chemotherapeutants are frequently used in salmonid aquaculture, and include formalin and antibiotics. Formalin solutions should not be discharged to the receiving ('host') lake. Formalin should therefore be only used within completely enclosed bags, and with wastewater disposal to approved sites (by tank truck and with disposal to approved tradewaste disposal facilities). Antibiotic use should be minimised. The potential for antibiotic impacts in deposited organic waste sediment has been recognised (Weston et al. 1996), but should be minimised by appropriate waste management. Antifouling chemicals should not be used in lake cage farms, due to the potential for off-site biological impacts. The established practice of mechanical washing and cleaning of fouled nets should be used instead, ensuring that net washing waste is not discharged to the lake environment and is appropriately managed by settling and land-based disposal.

Chemical use should be monitored by the keeping of a register of all chemicals used, their rates of use and records of individual treatments. All use of chemicals at a site should be listed in the site EPMP and reported to the regulatory authority (DPIWE Environmental Management Brach) prior to use, and approval sought. These reporting and approval requirements should be a condition of the site licence.

5.8 Best Practices Management Summary

In reviewing the use of cage systems in freshwater lakes, it is apparent that there has been a significant lack of development of environmentally focussed technology in the industry. Open-cage systems have been the dominant technology since the 1960's, and represent a cheap, 'dirty' technology. Some advances have been made in the area of improved feed quality and technology (eg extruded pellets), and in improving feeding efficiency (reducing feed losses), all advances that benefit production and coincidentally have environmental benefits. A significant issue still remains with solid waste and nutrient release however - an area that has received effectively no attention, largely due to the lack of regulatory strength or will in many salmonid producing countries. Industry has shown both the capacity and capability to introduce waste reduction and treatment technology in freshwater hatcheries, both overseas and in Tasmania. If lake cage culture is to be introduced into Tasmania with best practice environmental management, then it has to:

1. use active and proven waste treatment technologies;
2. minimise contact with the lake environment;
3. have production limits based on demonstrated levels of nutrient and solids emissions, coupled with lake mass-balance and nutrient-process models developed using Tasmanian data;
4. conduct monitoring and surveillance as an integrated part of its management.

If industry cannot comply with these requirements, particularly 1 and 2, then it must invest in the development and demonstration of appropriate technologies *prior* to becoming established in the freshwater environment. I would suggest that, with open-cage farming technologies, it will not be able to fully comply with the community's desire to maintain 'clean water', oligotrophic lake systems.

Lake cage salmonid culture represents a potential significant point source of nutrients and organic waste to freshwater lakes. The majority of Tasmanian lakes are highly oligotrophic, susceptible to eutrophication, and have high economic and social values for other purposes (eg recreational fishing, hydro power generation).

The application of best environmental management practice should result in:

1) lake cage culture not being allowed to proceed due to:

- the recognised significant contribution of open-system cage farms to organic and nutrient budgets of lakes;
- the recognised susceptibility of Tasmanian lakes to nutrient enrichment;
- observations of variable environmental performance overseas;
- the lack of tested technologies for controlling and minimising effluent discharges from cage farms; and
- poor control of possible future and current disease management issues.

or –

2) that if it be allowed to proceed, that it proceed initially:

- on a limited, pilot basis only (for a period of no less than five years), with a strong R&D, monitoring and planning focus, aimed at quantifying the environmental and natural resource risks posed by this industry sector, trialling waste minimisation technology, assessing initial environmental performance and consolidating appropriate planning and monitoring tools;

while

- industry, state and local government jointly prepare a best practice management (BPM) framework focussed on environmental outcomes and performance (taking into account those issues articulated in section 5 of this report), coupled with the development of appropriate planning tools (to be deployed within the context of the relevant Acts);

and -

3) that if further development were then to occur, that it be strongly controlled by appropriate planning, and 'input' and 'output' management tools within a BPM framework, and under a specific EPMP process, and with best technology, in order to:
   - exclude cage culture from that majority of Tasmanian lakes which is highly susceptible to risks posed by nutrient enrichment;
   - ensure that lake cage culture only occurred in those lakes with maximum water exchange, minimal susceptibility to eutrophication (see above), minimal conflict with other uses and in environmentally appropriate sites within lakes;
   - ensure that lake cage culture was as 'self contained' as possible, e.g. by the use of bag systems, with active effluent management including removal of waste solids and nutrients, coupled with regular site management including fallowing, and active removal of organic benthic sediment and/or with appropriate land-based waste treatment and disposal;

- control lake cage production by the use of biomass/production limits based on models of nutrient-algal relationships in Tasmanian lakes, combined with data on waste emission from pilot cage sites;
- place controls on feed quality (dust, N and P content, P assimilability, FCR) and feed quantity in order to minimise P and N an organic waste production;
- demonstrate that feeding is optimised to ensure minimal feed wastage and loss to the receiving environment (e.g. using Aquasmart technology);
- ensure that disease surveillance and management are an intimate part of operations, and that these activities also include surveillance of wild fish populations within the lakes;
- ensure the use of appropriately vaccinated fish stocks (e.g. for *Yersinia ruckeri* and *Vibrio anguillarum*);
- ensure that farms are designed to minimise predation problems and the need for intensive predator management;
- ensure that appropriate monitoring be conducted prior to and following site establishment (see above);
- ensure that associated practices (eg net washing) are conducted in an environmentally appropriate manner in order to minimise water quality impacts;
- ensure that licence conditions include the recognised need to place limits on biomass/production based on environmental conditions of the receiving environment.

It is my belief that the timing of the request by industry to expand cage aquaculture into the freshwater environment presents a unique opportunity for all stakeholders to provide an optimal environmental outcome, using best practice. The use of what is 30 - 40 year old technology, with uncontrolled waste release (i.e. open-cage culture) is not appropriate within a best environmental management practice framework, is not consistent with current industrial best practice, nor with the State Policy on Water Quality Management (SPWQM 1997), and should not be advocated either by industry or government.

It is also not equitable for an industry sector which releases untreated waste to freshwaters to commence operation at the same time as active steps are being taken at local and state government level to convert waste disposal from wastewater treatment plants to higher level technologies. The SPWQM's hierarchy of waste management focuses on reuse and recycling of waste waters, minimising waste production and only recommending waste disposal as a last option. A new lake cage culture industry should comply with that philosophy. Under best practice environmental management, the industry should not be established unless it can demonstrate the ability to actively manage its effluent, to a satisfactory level and with appropriate technology,.

If there is an agreement that lake cage culture will proceed, adequate time and resources must be made available, primarily by industry, in order to facilitate the development of high quality and 'best practice' industry environmental performance prior to this industry sector becoming fully established. The government must also be aware of the highly sensitive public nature of this development, and of the environmental risks associated with it, and must ensure that the best planning and regulatory tools are applied to it and are adequately resourced.

6. References

Axler R, Owen C, Ameel J, Ruzycki E and J Henneck 1994. Water quality issues associated with aquaculture: A case study in Minnesota Mine pit lakes. Lake Reservoir Management 9, 53.

Axler R, Tikkanen C, McDonald M and Larsen C and G Host 1993. Fish bioenergetics modeling to estimate waste loads from a net-pen aquaculture operation. In: *Techniques for Modern Aquaculture*. (Rang JK, ed.) American Society of Agricultural Engineers, Spokane WA, pp. 596 – 604.

Behmer DJ, Greil RW, Greil DC and BP Fessel 1993. Evaluation of cone-bottom cages for removal of solid wastes and phosphorus from pen-cultured rainbow trout. Progressive Fish Culturist 55, 255 – 260.

Bergheim A, Tyvold T and EA Seymour 1991. Effluent loadings and sludge removal from land based salmon farming tanks. *Proceedings of Aquaculture Europe '91: Aquaculture and the Environment International Aquaculture Conference*. Dublin Ireland, 1991. EAS Spec. Pubn. 14. EAS, Bredene Belgium.

Beveridge MCM 1984. Cage and Pen Farming: Carrying capacity models and environmental impact. FAO Fisheries Technical Paper 255, FAO Rome.

Carss DN 1990. Concentrations of wild and escaped fishes immediately adjacent to fish farm cages. Aquaculture 90, 29 – 40.

Cho CY, Hynes JD., Wood KR and HK Yoshida 1991. Quantification of fish culture wastes by biological (nutritional) and chemical (limnological) methods: the development of High Nutrient Dense (HND) diets. In: *Nutritional Strategies and Aquaculture Waste*. Proceedings of the 1st International Symposium on Nutritional Strategies in Management of Aquaculture Waste. University of Guelph, Ontario, Canada, 1990. (Cowey CB and CY Cho, eds.), pp. 251 – 262. Fish Nutrition Research Lab., Dept of Nutritional Sciences, University of Guelph Ontario.

Clarke R and M Phillips 1989. Environmental impacts of salmon aquaculture. AAC Bulletin Edition 89-4, 24 –30.

Cornell GE and FG Whoriskey 1993. The effects of rainbow trout (*Oncorhynchus mykiss*) cage culture on the water quality, zooplankton, benthos and sediment of Lac du Passage, Quebec. Aquaculture 109, 101 – 117.

Davies PE 1992. Nutrient-chlorophyll relationships in Tasmanian lakes. Presentation to the Australian Society for Limnology, Annual Conference 1989, Bronte Tasmania.

Dillon PJ and FH Rigler 1974. A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. J. Fish. Res. Bd .Can. 31, 1771 – 1778.

EAO 1997a. Salmon Aquaculture Review. Scotland. Vol. 4 Part C Chapter III. Environmental Assessment Office, British Columbia.

EAO 1997b. Salmon Aquaculture Review. Chile. Vol. 4 Part C Chapter VII. Environmental Assessment Office, British Columbia.

EAO 1997c. Salmon Aquaculture Review. Implications and trends relevant to British Columbia. Vol. 4 Part C Chapter VIII. Environmental Assessment Office, British Columbia.

Elberizon, IR and LA Kelly 1998. Empirical measurements of parameters critical to modelling benthic impacts of freshwater salmonid cage aquaculture. Aquaculture Research 29, 669 – 677.

Gavine FM, MJ Phillips and A Murray 1995. Influence of improved feed quality and food conversion ratios on phosphorus loadings from cage culture of rainbow trout *Oncorhynchus mykiss* (Walbaum), in freshwater lakes. Aquaculture Research 26, 483 – 495.

Gowen RJ and NB Bradbury 1987. The ecological impact of salmonid farming in coastal waters: a review. Oceanogr. Mar. Biological. Ann. Rev. 25, 563 – 575.

Harvey J and LM Laird 1988. Farming trout and salmon in fresh water cages. In: *Salmon and Trout Farming* (Needham T, ed.) pp. 190 – 201.

Ingram BA (Ed) 1999. *Towards best practice in land-based salmonid farming. Options for treatment, re-use and disposal of effluent.* Proceedings of a workshop held at Eildon 28 April 1998. Marine and Freshwater Resources Institute, 1999.

Jensen JB 1991. Environmental regulation of freshwater fish farms in Denmark. In: *Nutritional Strategies and Aquaculture Waste*. Proceedings of the 1st International Symposium on Nutritional Strategies in Management of Aquaculture Waste. University of Guelph, Ontario, Canada, 1990. (Cowey CB and CY Cho, eds.), pp. 251 – 262. Fish Nutrition Research Lab., Dept of Nutritional Sciences, University of Guelph Ontario.

Johannessen PJ, Botnen HB and F Tvedten 1994. Macrobenthos: before, during and after a fish farm. Aquaculture and Fisheries Management 25, 55 – 66.

Johnson F and A Wandsvik 1991. The impact of high energy diets on pollution control in the fish framing industry. In: *Nutritional Strategies and Aquaculture Waste*. Proceedings of the 1st International Symposium on Nutritional Strategies in Management of Aquaculture Waste. University of Guelph, Ontario, Canada, 1990. (Cowey CB and CY Cho, eds.), pp. 51 – 64. Fish Nutrition Research Lab., Dept of Nutritional Sciences, University of Guelph Ontario.

Kelly LA 1995. Predicting the effect of cages on nutrient status of freshwater lochs using mass-balance models. Aquaculture Research 26, 469 – 477.

Kelly LA and SJ Cripps 1999a. Options and imperatives for salmonid effluent management In: *Towards best practice in land-based salmonid farming. Options for treatment, re-use and disposal of effluent.* Proceedings of a workshop held at Eildon 28 April 1998. Ingram BA (Ed). Marine and Freshwater Resources Institute, 1999.

Kelly LA and SJ Cripps 1999b. Environmental issues and regulations in European aquaculture. In: *Towards best practice in land-based salmonid farming. Options for treatment, re-use and disposal of effluent.* Proceedings of a workshop held at Eildon 28 April 1998. Ingram BA (Ed). Marine and Freshwater Resources Institute, 1999.

Kelly LA, Stellwagen J and A Bergheim 1996. Waste loadings from a freshwater atlantic salmon farm in Scotland. Water Resources Bulletin, AWRA 32, 1017 – 1025.

Korzeniewski K, Trojanowksi J and C Trojanowska 1985. Hydrochemical study of lake Szczytno Male with trout cage culture. Polskie Arch. Hydrobiologii 32, 157 – 174.

Maloney D, Gillooly M, Costello M and J Wilson 1991. Water quality and sediment nutrients around salmon cages in a freshwater lake. In: *Aquaculture and the Environment.* EAS Special Pubn. No. 14, 202 – 203.

Massik Z and MJ Costello 1994. Bioavailability of phosphorus in fish farm effluents to freshwater phytoplankton. Proceedings of an International Symposium: *Aquaculture and Water Resource Management* (Kelly LA, MCM Beveridge, DJ Baird and JF Muir, eds.) 26, 607 – 616.

McLay A and K Gordon-Rogers (Eds.) 1997. Report of the Scottish Salmon Strategy Task Force. Scottish Agriculture, Environment and Fisheries Department, Edinburgh.

Merican ZO and MJ Phillips 1985. Solid waste production for rainbow trout, *Salmo gairdneri* Richardson, cage culture. Aquaculture and Fisheries Management 1, 55 – 69.

NCC 1990. *Fish Farming and the Scottish Freshwater Environment*. A report to the Nature Conservancy Council. Institute of Aquaculture, Institute of Freshwater Ecology, Institute of Terrestrial Ecology. 285 pp.

OECD 1982. *Eutrophication of Waters, Assessment and Control.* Organisation for Economic Co-operation and Development Paris.

Penczak T, Galicka W, Molinski M, Kusto E and M Zalewski 1982. The enrichment of a mesotrophic lake by carbon, phosphorus and nitrogen form the cage aquaculture of rainbow trout, *Salmo gairdneri*. J. Applied Ecol. 19, 371 – 393.

Phillips MJ 1985. The environmental impact of cage culture in Scottish freshwater lochs. Unpubl. Report to the Highlands and Island Development Board. Institute of Aquaculture, University of Stirling, Stirling UK.

Phillips MJ, Beveridge MCM and JA Stewart 1986. The environmental impact of cage culture on Scottish freshwaters. In: Solbe JF de LG (Ed) Effects of land use on fresh waters: agriculture, forestry mineral exploitation, urbanisation, Ellis Horwood, Chichester 568 pp, 504 – 508.

Phillips MJ, Beveridge MCM and LG Ross 1985. The environmental impact of salmonid cage culture on inland fisheries: present status and future trends. J. Fish. Biological. 27 (Supp. A), 123 – 137.

Riley ET and EE Prepas 1985. Comparison of the phosphorus-chlorophyll relationships in mixed and stratified lakes. Can J Fish Aquat. Sci. 42, 831-835.

Sanger A 1992. Inland Fisheries Commission Biological Consultancy. Annual Report to the Hydro Electric Commission. pp. 91. HEC/IFC Hobart.

Scottish Executive 1999. Press Release 1999. www.Scotland.gov.uk/news/press1999.

SEPA 1997. Total phosphorus water quality standards for Scottish freshwater lochs. Scottish environmental Protection Agency, Policy 16. Dingwall Scotland.

Stirling HP and T Dey 1990. Impact of intensive cage fish farming on the phytoplankton and periphyton of a Scottish freshwater lake. Hydrobiologia 190, 193 – 214.

Bowling LC, Steane MS and PA Tyler 1986. The spectral distribution and attenuation of underwater irradiance in Tasmanian inland waters. Freshwater Biology 16, 313 – 335.

Vollenweider RA 1969. Mögichkeiten und grenzen elementarer modelle der stoffebilanz von seen. Archiv für Hydrobiologie. 66 1 – 36.

Wee KL 1999. Role of feeds in reducing nutrient load in effluent from salmonid farms. In: *Towards best practice in land-based salmonid farming. Options for treatment, re-use and disposal of effluent.* Proceedings of a workshop held at Eildon 28 April 1998. Ingram BA (Ed). Marine and Freshwater Resources Institute, 1999.

Weston DP, Phillips MJ and LA Kelly 1996. Environmental impacts of salmonid culture. Chapter 16 in: *Principals of Salmonid Culture.* Developments in Aquaculture and Fisheries Science 29, 919-967.

Williamson RB and MCM Beveridge 1994. Fisheries and Aquaculture. In: *Freshwaters of Scotland.* (Maitland P, Boon PJ and DJ McClusky, eds.), pp. 317 – 322. John Wiley and Sons Ltd Chichester.